High-precision Study of Weak Interaction with Neutrons

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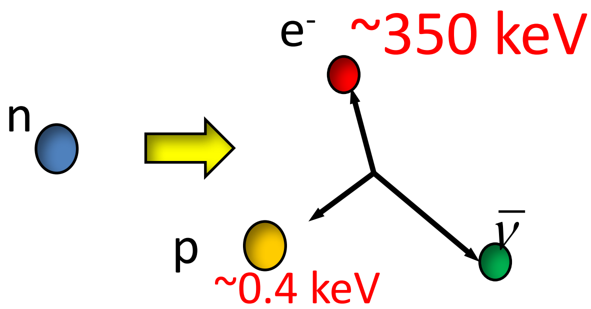
International Workshop on Neutrino Nuclear Responses for Double Beta Decays and Astro-Neutrino Interactions (NNR16)
September 29-30, 2016, RCNP, Osaka University

Topics

- Neutron beta decay
  - Neutron lifetime
  - Weak axial vector coupling $\lambda = g_A/g_V$
- Experiment with J-PARC pulsed neutron
  - Measurement of neutron lifetime
  - Measurement of $^{14}N(n,p)^{14}C$ reaction cross section

Neutron lifetime

Neutron beta decay lifetime



Neutron lifetime :

τ_n = 880.3 ± 1.1 （PDG2014）

τ_n = 880.1 ± 1.1 （PDG2012）

τ_n = 881.5 ± 1.5 （PDG2011）

τ_n = 885.7 ± 0.8 （PDG2010）

The neutron decays into the proton, the electron, and the anti-neutrino in 880 sec. This is the simplest nuclear beta decay.

The neutron lifetime is important to

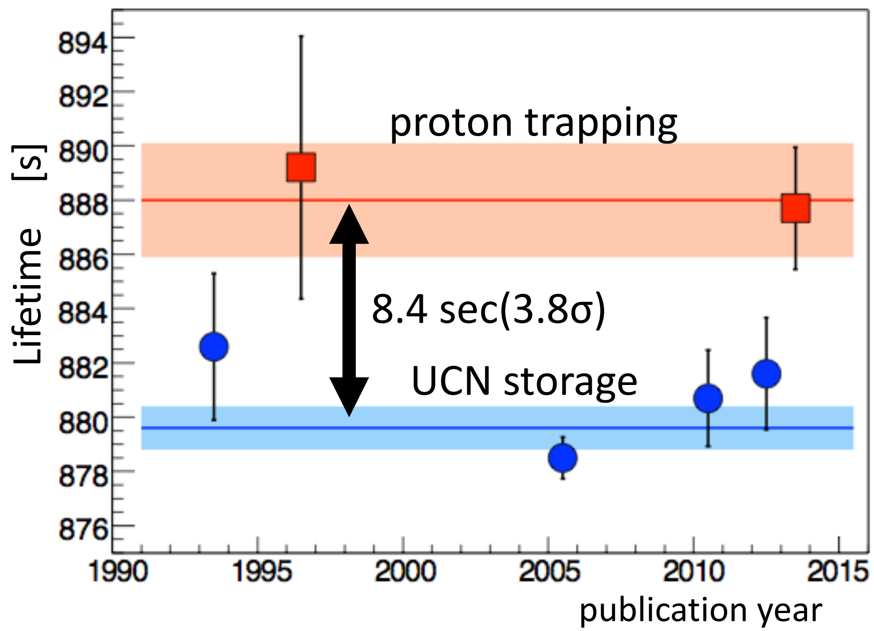
- Big Bang Nucleosynthesis
- Reactor neutrino anomaly
- Solar neutrino
- CKM unitarily
- Proton spin
- Goldberger-Treiman/Muon caputre
- Bjorken sum rule
- Lattice calculation benchmark

Neutron Lifetime

Neutron lifetime is an important parameter for both of particle physics and cosmology.

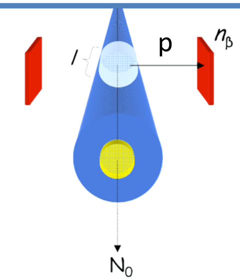
880.3±1.1s (PDG2015)

There is 8.4sec (3.8σ) deviation of the value of lifetime between two methods of measurement.



A.T. Yue et. al., PRL 111, 222501 (2013)

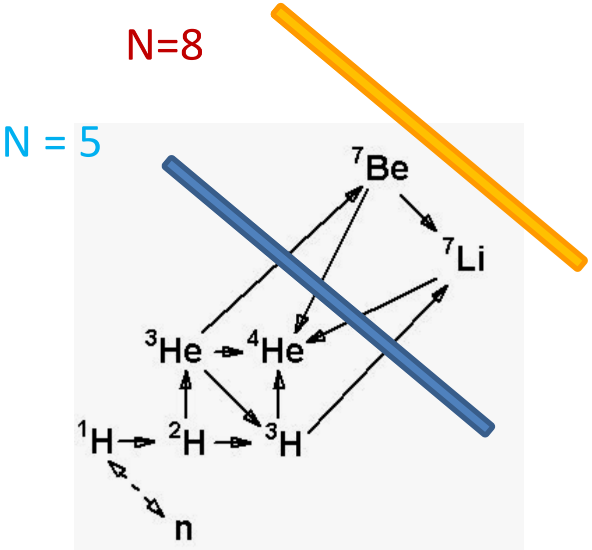
In-beam method
Count the dead



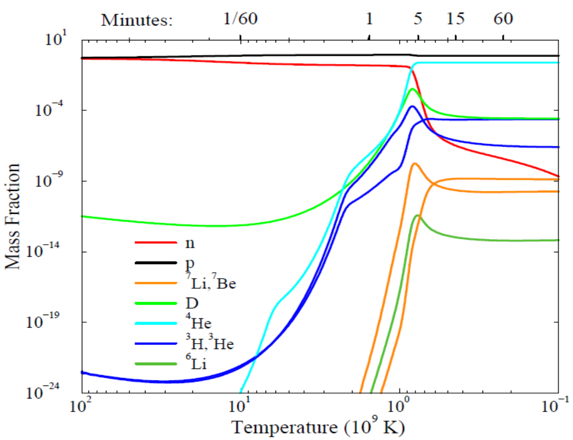
Storage method
Count the living

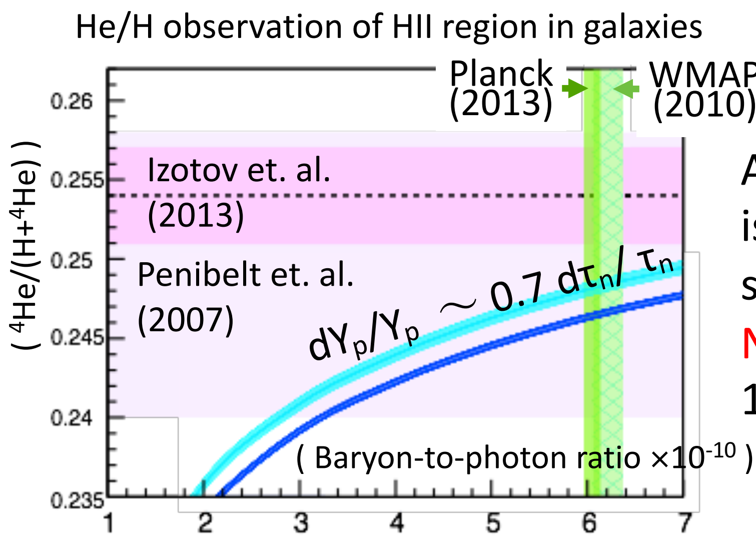
Big bang nucleosynthesis

CMB & He/H & Neutron Lifetime



Light elements up to N=7 were created in 3 minute after the big bang (Big Bang Nucleosynthesis). Abundance of them can be calculated by baryon-to-photon ratio, nuclear cross sections, and **the neutron lifetime**.



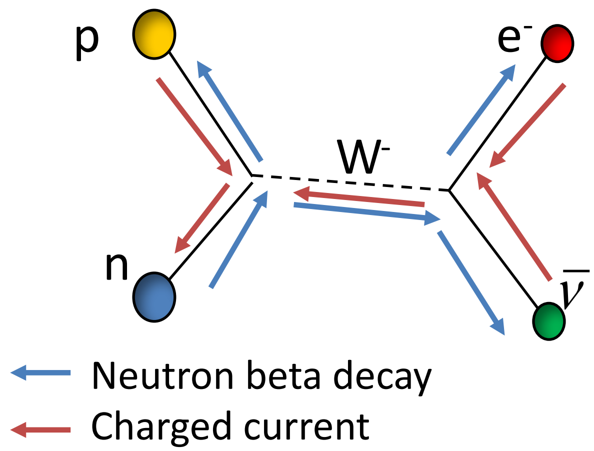


A recent observation[1] is not consistent with standard cosmology.
$N_{eff} = 3.51 \pm 0.35$,
1.5 σ deviation from 3.

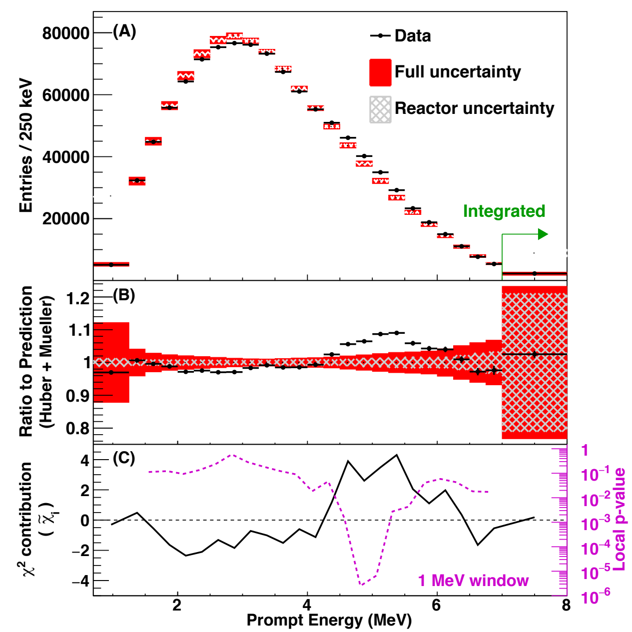
CMB+BAO observation[2] Independently result
$N_{eff} = 3.43 \pm 0.26$, which has 1.7σ deviation from 3.
We may missing something in the early universe.

1. Izotov, Y. I., G. Stasińska, and N. G. Guseva. "Primordial 4He abundance: a determination based on the largest sample of H II regions with a methodology tested on model H II regions." *Astronomy & Astrophysics* 558 (2013): A57.
2. Aubourg, Éric, et al. "Cosmological implications of baryon acoustic oscillation measurements." , *Physical Review D* 92.12 (2015): 123516.

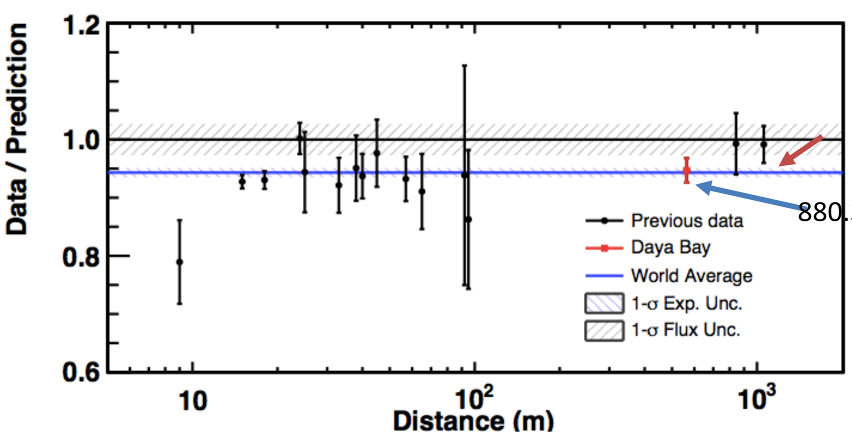
Reactor antineutrino anomaly



Neutrino charged-current interactions with proton is well used reaction for neutrino water Cherenkov detector. It is the inversed reaction of the neutron beta decay, thus the cross section is calculated by the neutron lifetime.



Recent reactor neutrino measurements observed 94.3±2.4%. Neutron lifetime of 8 sec contribute 1% change.



If 888 sec, it goes 1% up.

880.3(1.1) sec

Energy spectrum of reactor antineutrino has Bump at 5 MeV more than 4 σ.
We are surely missing something!

An, F. P., et al. "Improved Measurement of the Reactor Antineutrino Flux and Spectrum at Daya Bay." *arXiv preprint arXiv:1607.05378* (2016).

The weak axial vector coupling $\lambda = g_A/g_V$

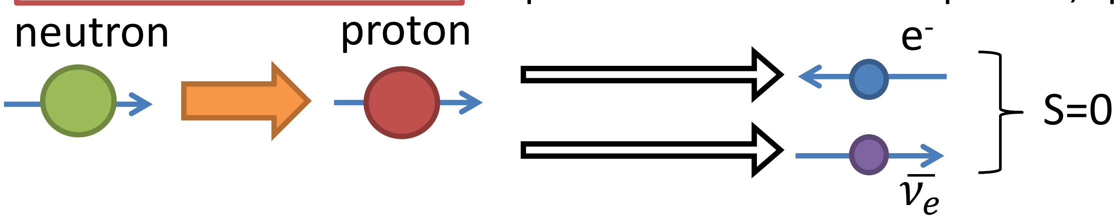
Fermi and Gamow-Teller decay

- Nuclear beta decay has 2 types, Fermi and GT decay.

S: Spin angular momentum
L: orbital angular momentum
J: Angular momentum of nucleus

Fermi (Vector) decay

Spins of e- and ν are anti-parallel, spin of proton and neutron are parallel

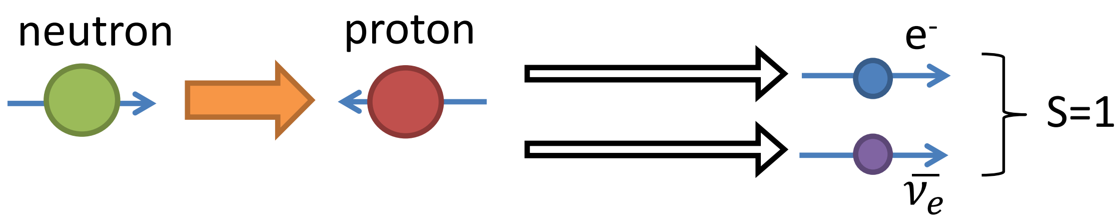


$\Delta S=0$
$\Delta L=0$
$\Delta J=0$

Coupling constant
$g_V=G_FV_{ud}$

Gamow-Teller (Axial Vector) decay

Spins of e- and ν are parallel, spin of proton and neutron are parallel



$\Delta S=1$
$\Delta L=0$
$\Delta J=1$

Coupling constant
$g_A=\lambda G_FV_{ud}$
$\lambda=g_A/g_V=1.27\ldots$

Gamow-Teller has ~27% larger coupling constant due to violation of the chiral symmetry. The value called, $\lambda=g_A/g_V$, is experimentally determined by measuring an asymmetry parameter of the neutron beta decay.

Decay parameters of the polarized neutron

Can be described by λ parameter in standard model.

$$d\Gamma \propto \mathcal{N}(E_e)\Big\{1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\frac{\Gamma m_e}{E_e} + \langle\vec{J}\rangle\cdot\Big[\boxed{A}\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\Big] + \vec{\sigma}\cdot\Big[N\langle\vec{J}\rangle + G\frac{\vec{p}_e}{E_e} + Q'\hat{p}_e\hat{p}_e\cdot\langle\vec{J}\rangle + R\langle\vec{J}\rangle \times\frac{\vec{p}_e}{E_e}\Big]\Big\}d\Omega_e d\Omega_\nu dE_e,$$

$$\mathcal{N}(E_e) = p_eE_e(E_0 - E_e)^2;\ E_e\ (E_\nu),\ \vec{p}_e\ (\vec{p}_\nu)$$

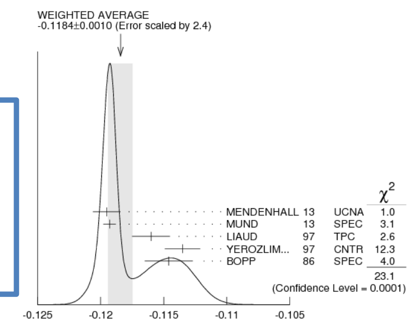
$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} \qquad \boxed{A = -2\frac{|\lambda|\cos\phi + |\lambda|^2}{1+3|\lambda|^2}}$$

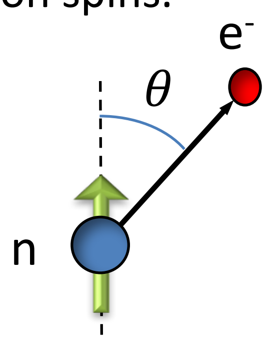
$$B = -2\frac{|\lambda|\cos\phi - |\lambda|^2}{1+3|\lambda|^2} \qquad D = 2\frac{|\lambda|\sin\phi}{1+3|\lambda|^2}$$

$$\tau = \frac{K/\ln 2}{V_{\mathrm{ud}}^2 G_{\mathrm{F}}^2(1+\lambda^2)f}$$

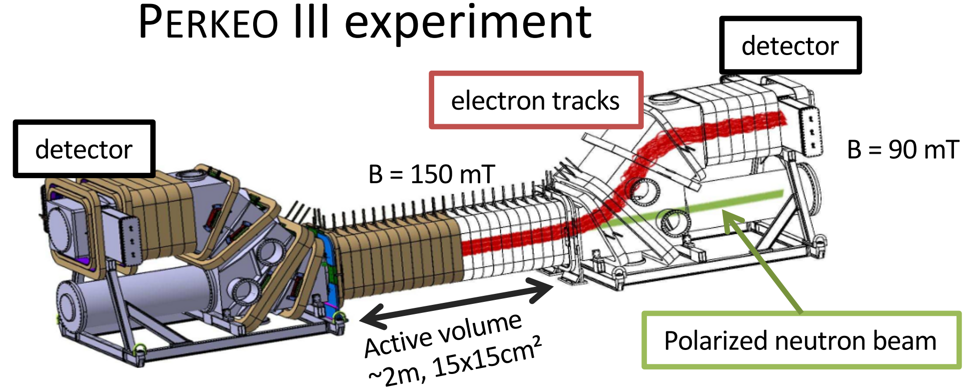
The β-Asymmetry Parameter A is the most sensitive for λ parameter, which can measured by energy and angular distribution of electrons against neutron spins.

PDG2014
A=**−0.1184±0.0010**
λ =**−1.2723±0.0023**





PERKEO III experiment



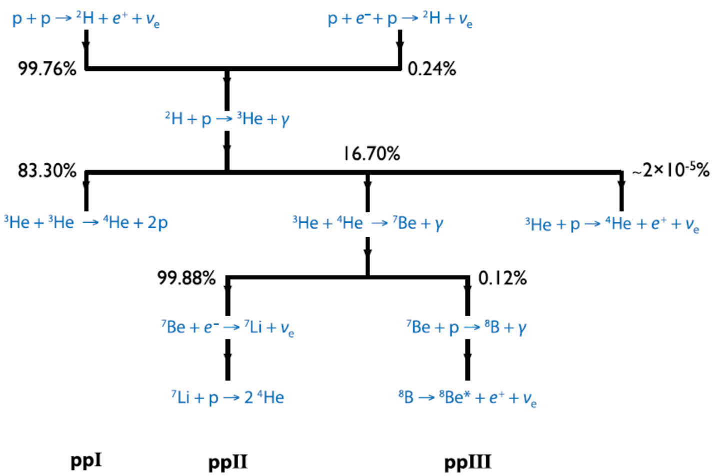
Mund, D., et al. "Determination of the Weak Axial Vector Coupling λ= g A/g V from a Measurement of the β-Asymmetry Parameter A in Neutron Beta Decay." *Physical review letters* 110.17 (2013): 172502.

Nuclear reaction in the sun

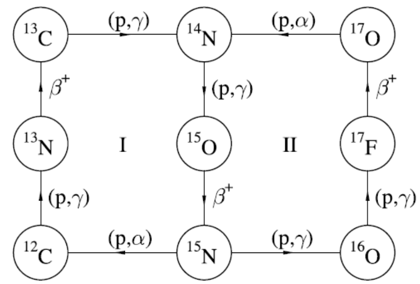
pp-chain and CNO cycle

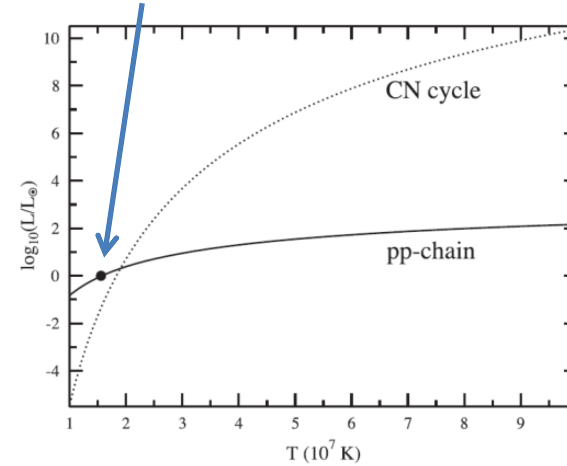
In the sun, energy of 99% is produced by pp-chain.
$p+p \rightarrow d+e^{+}+\nu_e$ is the most important.

pp-chain



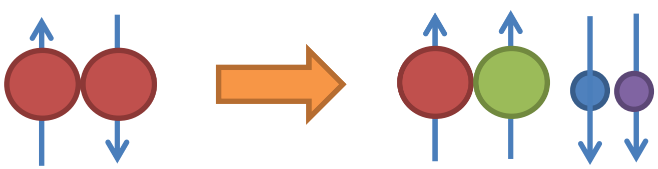
CNO





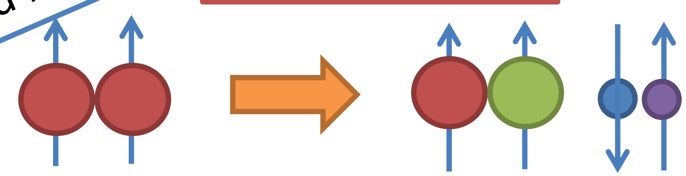
For $p+p \rightarrow d+e^{+}+\nu_e$, Fermi decay is excluded. Thus, this reaction is pure Gamow-Teller (g_A)decay.
λ value is necessary to calculate the cross section.

Gamow-Teller decay(g_A)



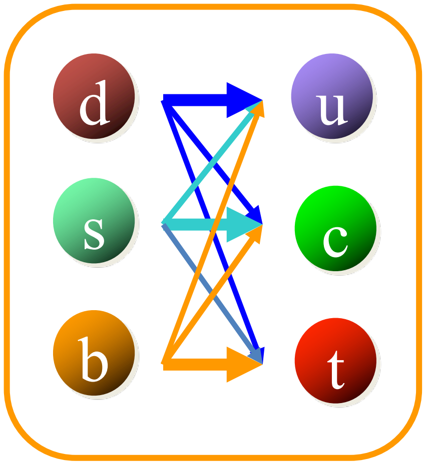
Excluded by Pauli principle

Fermi decay(g_V)



Adelberger, E. G., et al. "Solar fusion cross sections. II. The p p chain and CNO cycles." *Reviews of Modern Physics* 83.1 (2011): 195.

Neutron decay for V_{ud} in CKM-matrix



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{\mathrm{CKM}} = \begin{pmatrix} \boxed{0.97427 \pm 0.00014} & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

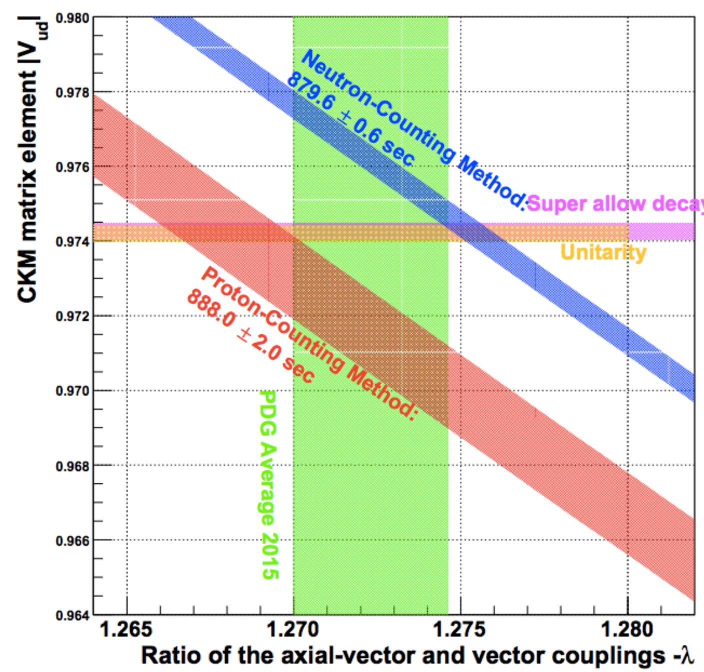
PDG2014

V_{ud} in CKM matrix is most precisely determined by nuclear $0^+ \rightarrow 0^+$ beta decay lifetimes. Unitarily of CKM matrix gives important information to the standard model.

V_{ud} can be calculate by neutron lifetime and λ parameter independent in nuclear models.

$$|V_{ud}|^2 = \frac{(4908.7 \pm 1.9)s}{\tau_n (1 + 3\lambda^2)},$$

W. J. Marciano and A. Sirlin, Phys. Rev. Lett. 96, 032002 (2006)



Experiment with J-PARC pulsed neutron

Collaborators

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The Univ. of Tokyo[1], Nagoya Univ.[2], KEK[3], ICR, Kyoto Univ.[4], KMI, Nagoya Univ.[5], Kyoto Univ.[6], Kyushu Univ.[7], CERN[8], RCAPP, Kyushu Univ.[9], J-PARC Center, Japan Atomic Energy Agency[10], RCNP, Osaka Univ.[11], GCRC, The Univ. of Tokyo[12], ICEPP, The Univ. of Tokyo[13]

Measurement of neutron lifetime

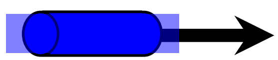
Principle of our experiment

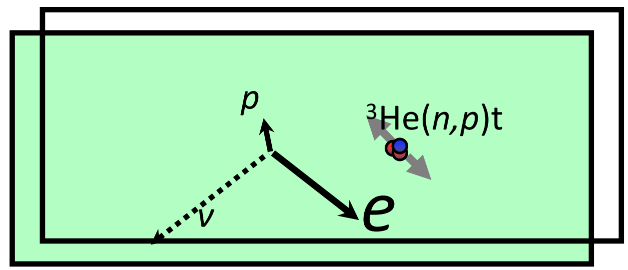
Cold neutrons are injected into a TPC.
The neutron β-decay and the $^{3}He(n,p)^{3}H$ reaction are measured simultaneously.

Principle (Kossakowski,1989)

Count events during time of bunch in the TPC

Neutron bunch shorter than TPC





Neutron bunch

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

β-decay $\quad S_\beta = \epsilon_e N \dfrac{L}{\tau_n v}$

$^{3}He(n,p)^{3}H$ $\quad S_n = \epsilon_n N \rho \sigma L$

τ_n : lifetime of neutron
v : velocity of neutron
ε_e : detection efficiency of electron
ε_n : detection efficiency of ^{3}He reaction
ρ : density of ^{3}He
σ : cross section of ^{3}He reaction

$$\sigma v = \sigma_0 v_0$$

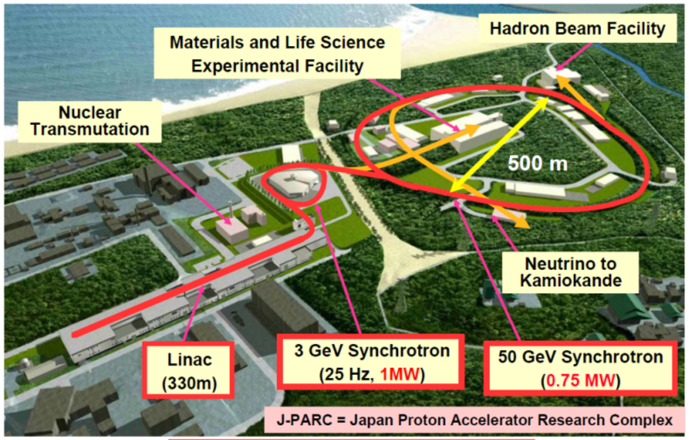
σ_0=cross section@v_0, v_0=2200[m/s]

This method is free from the uncertainties due to external flux monitor, wall loss, depolarization, etc.

Our goal is measurement with 1 sec uncertainty.

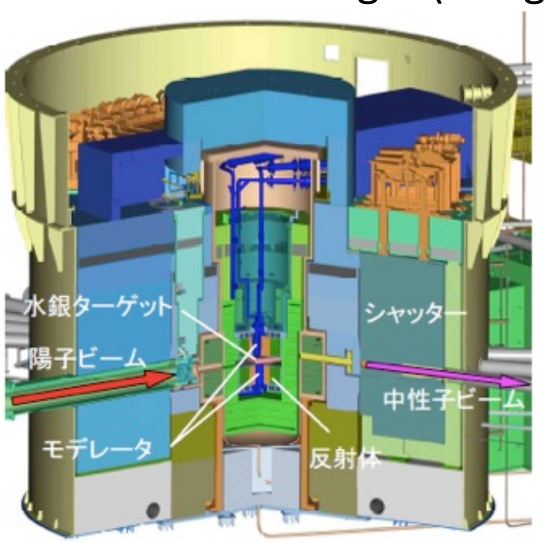
J-PARC / MLF / BL05

J-PARC
Materials and Life Science Experimental Facility(MLF)



Joint Project between KEK and JAEA

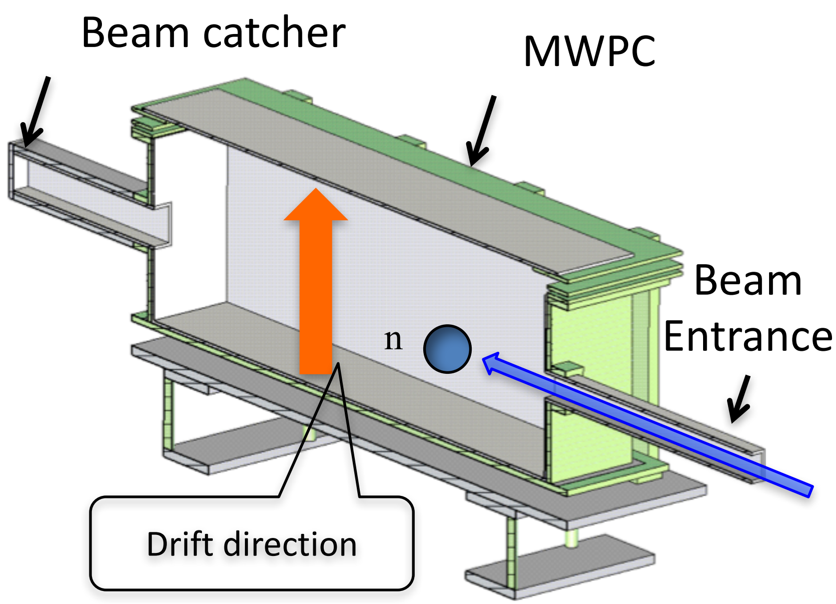
Spallation neutron target (designed for1MW)

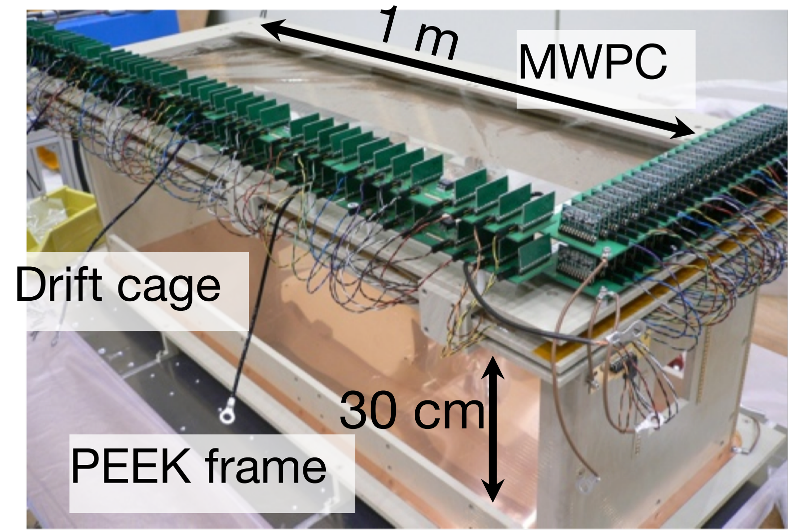


pulsed neutron Beam line BL05
Neutron optics and physics(NOP)

Time Projection Chamber(TPC)

High efficiency and Low background TPC is used beta and ^{3}He(n,p)^{3}H detection.

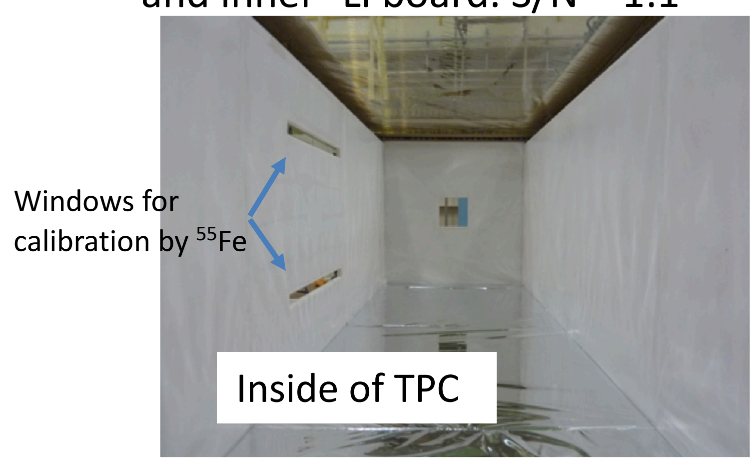




Trigger efficiency for beta >97%
for ^{3}He(n,p)^{3}H > 99.9%

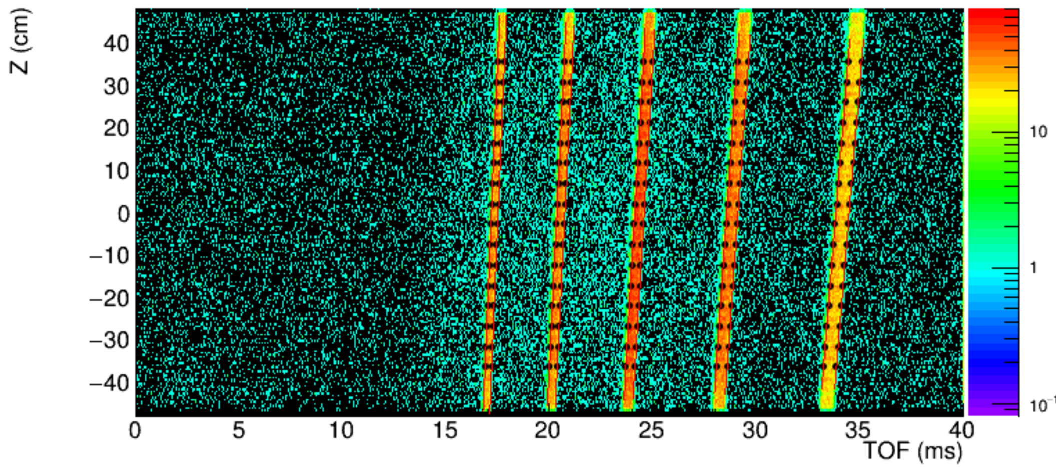
Anode wire	29 of W-Au wires(+1720V)
Field wire	28 of Be-Cu (0V)
Cathode wire	120 of Be-Cu (0V)
Drift length	30 cm (-9000V)
Gas mixture	He:CO2=85kPa:15kPa
TPC size(mm)	300,300,970

Low background with PEEK frame and inner ^{6}Li board. S/N ~ 1:1

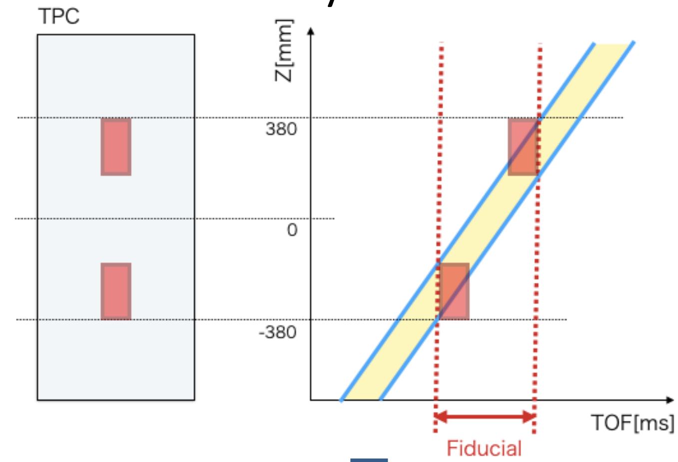


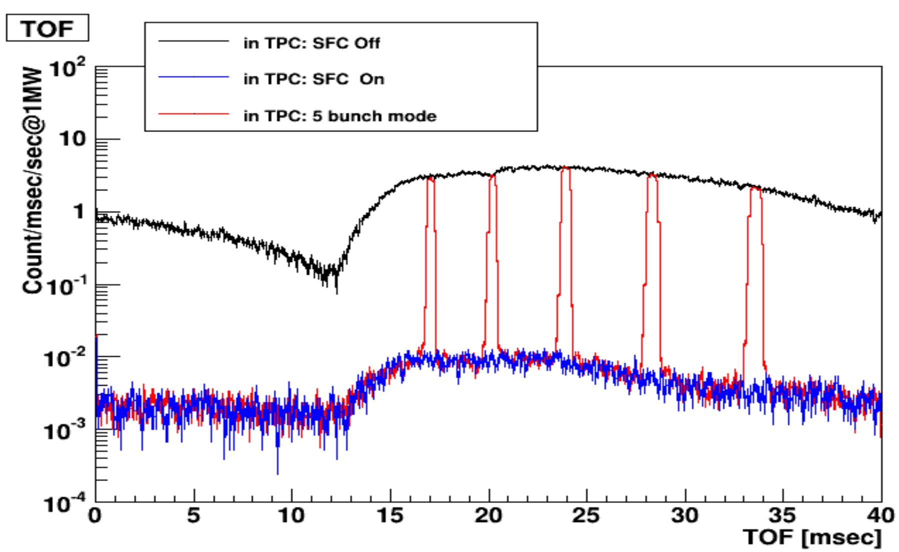
Neutron bunches in TPC

TOF vs. Z position (^{3}He)

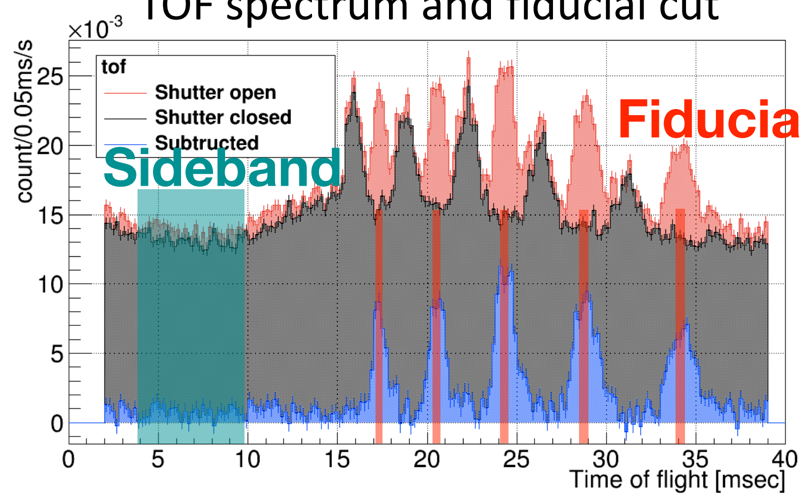


Neutron only in fiducial of the TPC are used for analysis.





TOF spectrum and fiducial cut



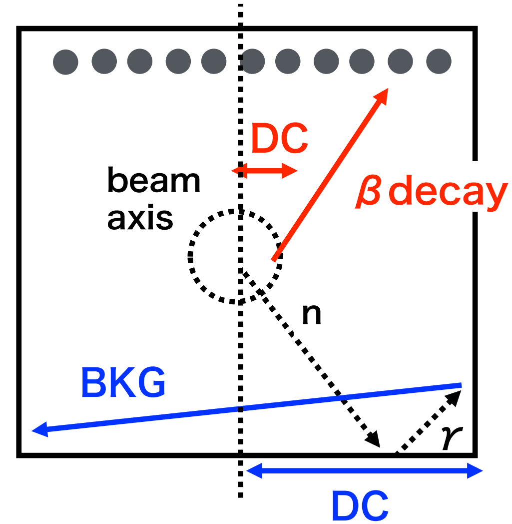
Spectrum of beta decay and Beam-induced background

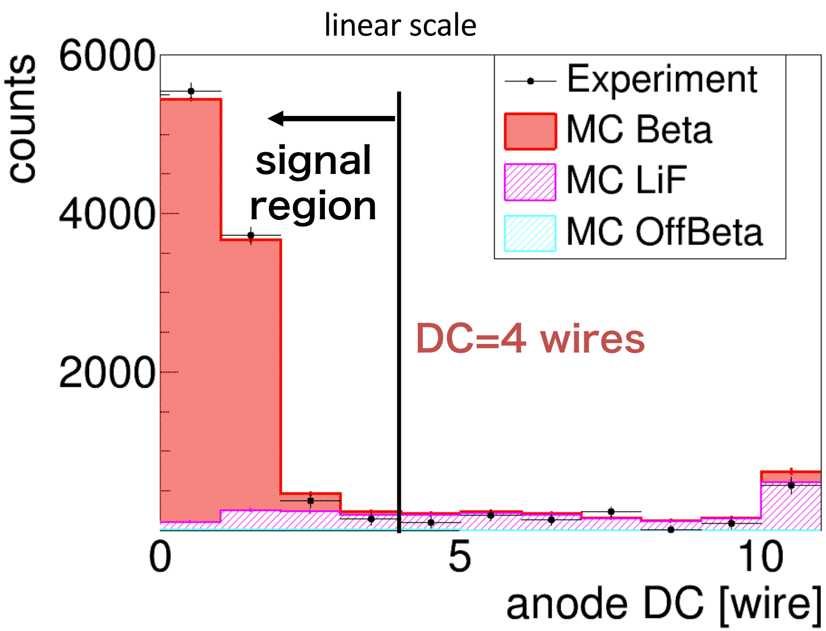
origin of the background is near TPC wall

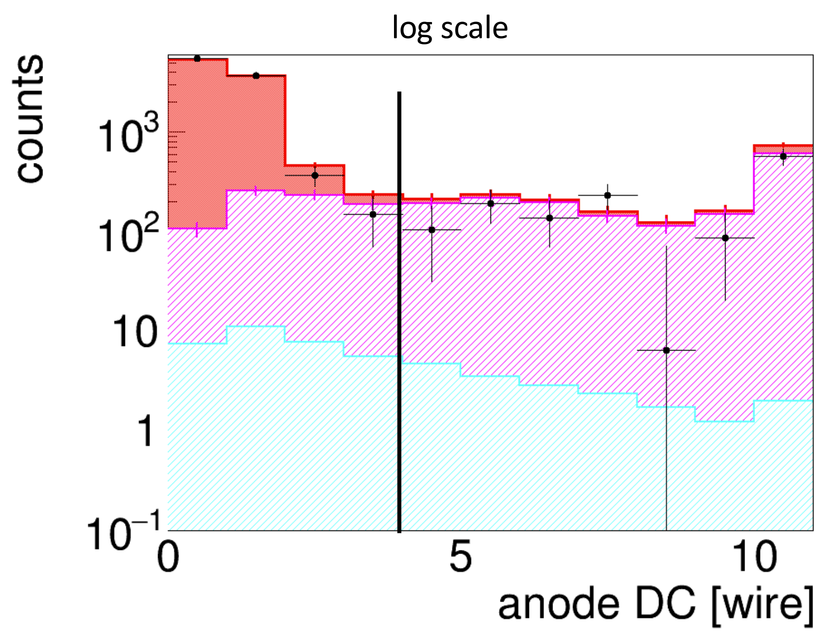
“DC"

<u>D</u>istance from beam <u>C</u>enter

background has large DC value



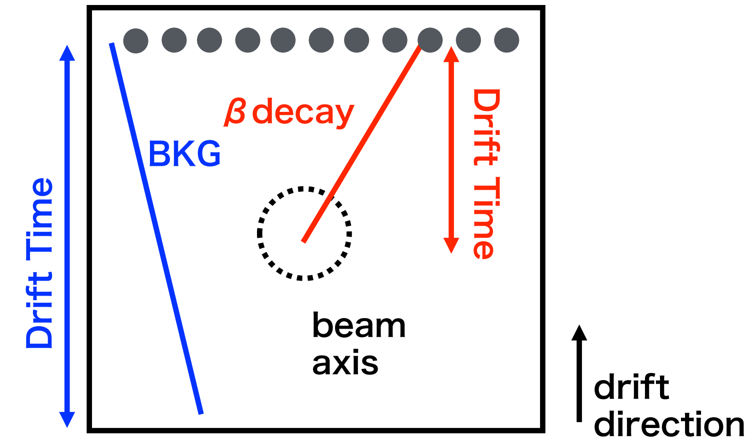


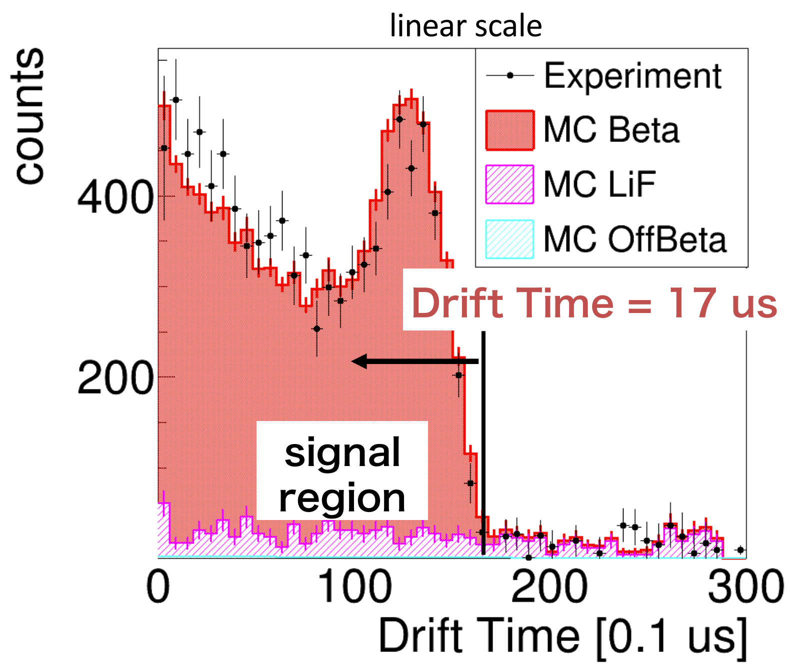


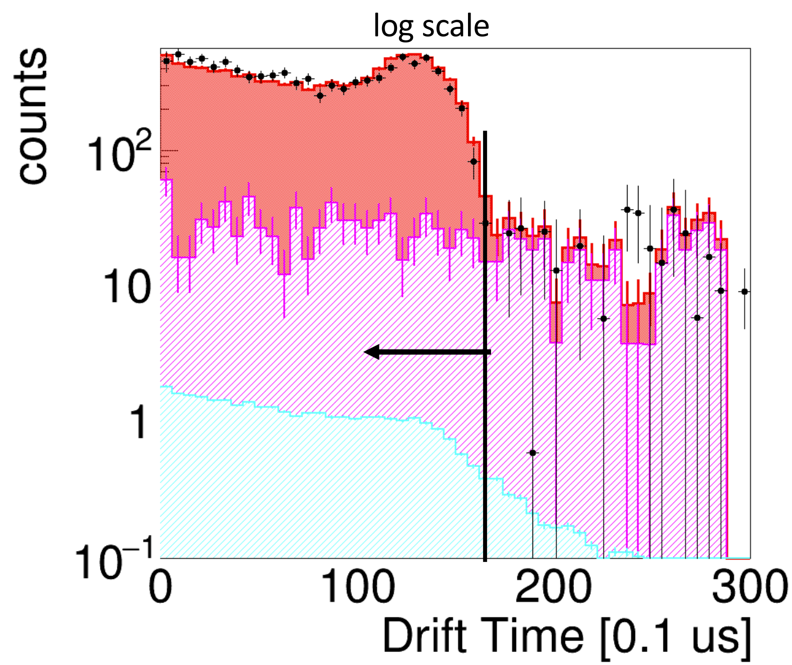
Spectrum of beta decay and Beam-induced background

origin of track is near TPC wall

"Drift Time"
arrival time difference of drifting electrons
background has long DriftTime







List of uncertainties

$$\tau_n = \frac{1}{\rho\sigma_0 v_0}\left(\frac{S_n/\epsilon_n}{S_\beta/\epsilon_\beta}\right)$$

σ_0	^{3}He(n,p)^{3}H cross section for a 2200 m/s neutron
v_0	2200 m/s (neutron velocity)
ρ	^{3}He number density
N_β	number of β decay events
$N_{^3\mathrm{He}}$	number of ^{3}He(n,p)^{3}H events
ε	selection efficiency

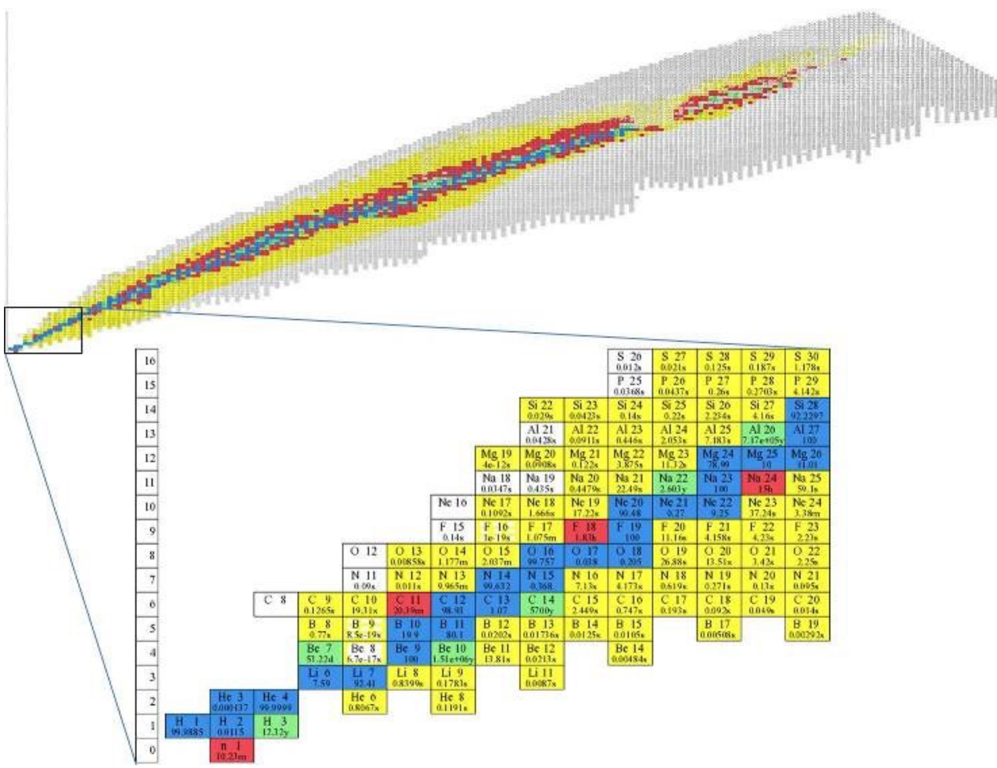
		correction (%)	uncertainty (%)
N_β	statistics		~ 1
	^{3}He(n, p)^{3}H leakage	0	< 0.34
	beam-induced background	8.6	being evaluated
	efficiency	6.1	$^{+1.0}_{-0.3}$
	pileup	-0.39	0.39
	background subtraction	-0.43	0.28
$N_{3\mathrm{He}}$	^{14}N(n,p)^{14}C contamination	-1.45	0.23
	^{17}O(n,α)^{14}C contamination	-0.5	0.03
N_β, $N_{3\mathrm{He}}$	Spin Flip Chopper S/N	< 0.5	< 0.5
ρ	^{3}He number density		0.65
	chamber deformation (pressure)	<0.33	<0.33
	temperature non-uniformity	0.23	0.23
σ_0	^{3}He(n, p)^{3}H cross section		0.13

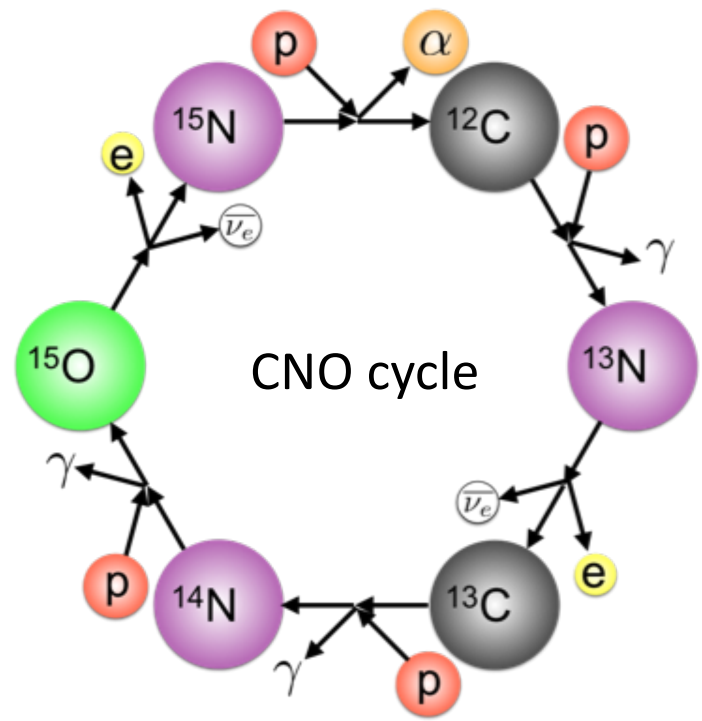
preliminary

Measurement of $^{14}N(n,p)^{14}$ reaction cross section

$^{14}N(n,p)^{14}C$ in astrophysics

In s-process, neutron capture reaction is called as neutron poison. ^{14}N is a major production in CNO cycle, thus, $^{14}N(n,p)^{14}C$ reaction is important.





https://www.jicfus.jp/jp/promotion/pr/mj/2011-4/

(n,p) reactions

- (n,p) reactions, like $^{3}He(n,p)^{3}H$ and $^{14}N(n,p)^{14}C$ have same initial and final state of inversed reaction of beta decay.

  $^{14}N + n \rightarrow {}^{14}C + p + 624$ keV

  $^{14}N + e^{-} \leftarrow {}^{14}C + \nu_e - 156$ keV

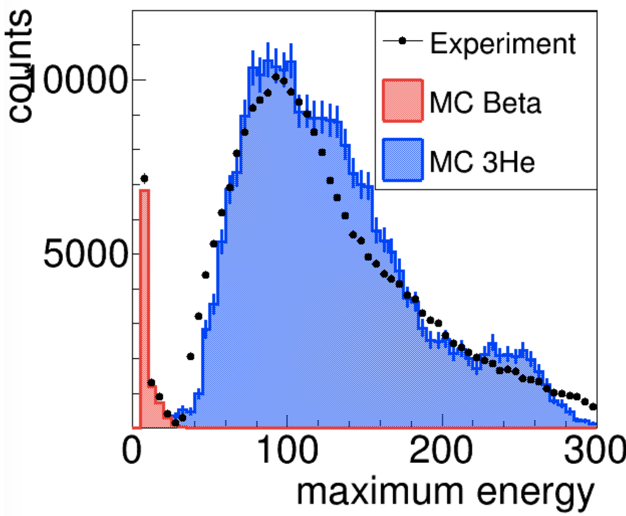
- They are not weak interactions. But CAN they help to understand beta decay reactions?

- We could measure $^{14}N(n,p)^{14}C$ reaction cross section using the TPC with 0.3%.

$^{14}N(n, p)^{14}C$ event in lifetime experiment

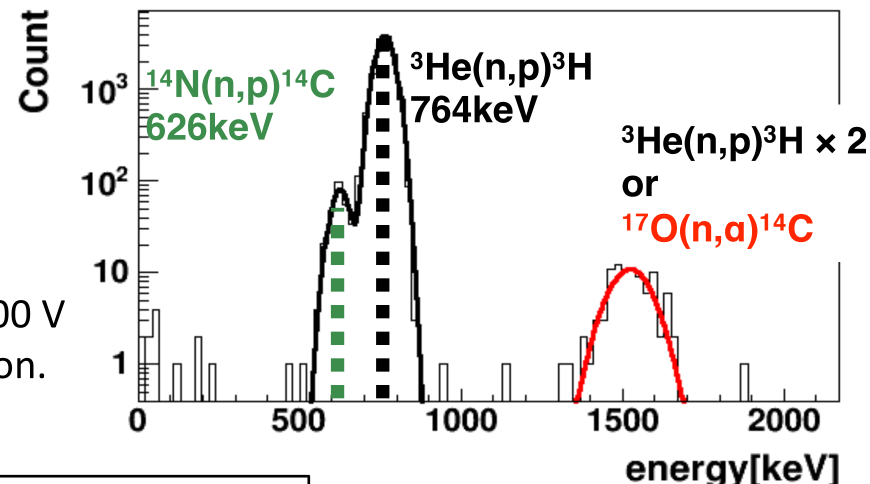
Because the TPC is used in sealed condition, contamination of ^{14}N was observed in bad vacuum. Low anode voltage measurements were done for identification of ^{14}N to avoid distortion by space charge effect.

1720 V for electron detection

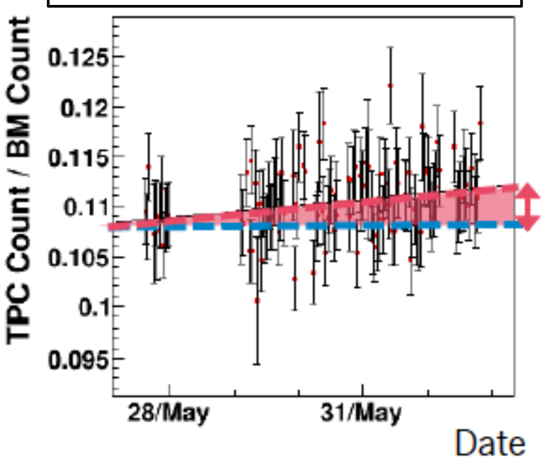


Anode voltage reduced to 1200 V for ion detection.

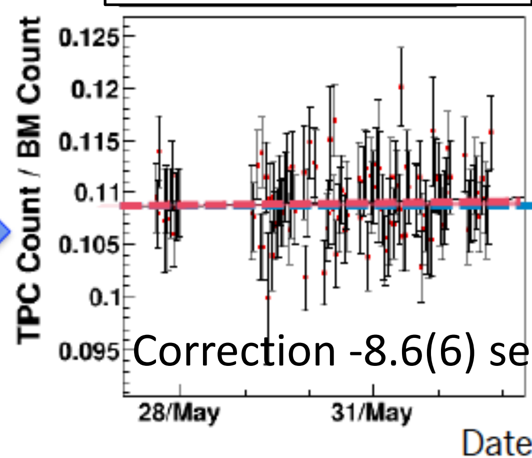
1200 V for electron detection



Before ^{14}N correction



After ^{14}N correction



Correction -8.6(6) sec

The correction was successfully done!
We could determined amount of ^{14}N.

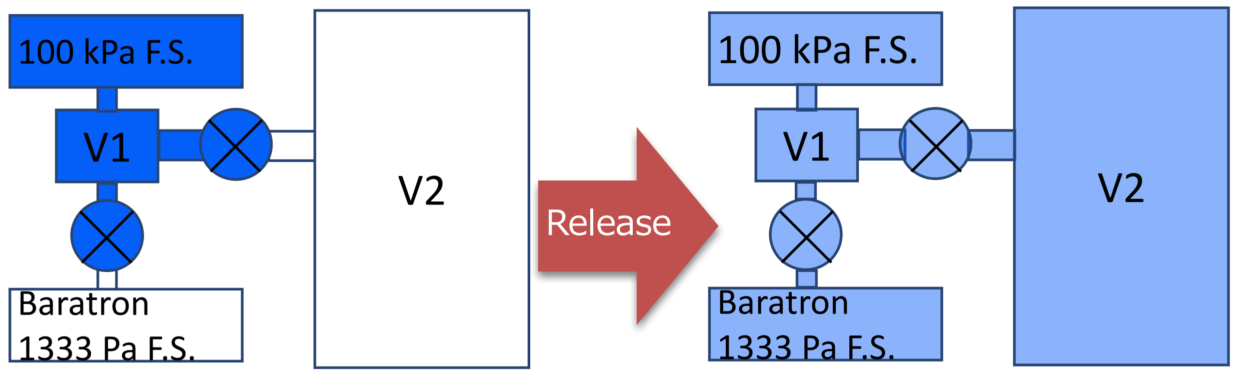
→ We measure the cross section with controlled N_2 gas!

Fabrication of TPC gas

TPC gas N_2 : ^4He : ^3He = 20kPa : 80kPa : ~10Pa

Procedure to fabricate TPC gas

0. Measure V1/V2 ratio.
1. Inject ^3He in MV1.
2. Release ^3He gas in V2(TPC).
3. Inject N_2, ^4He in V1 and V2.



Measured Gas fill, determined by 2 method

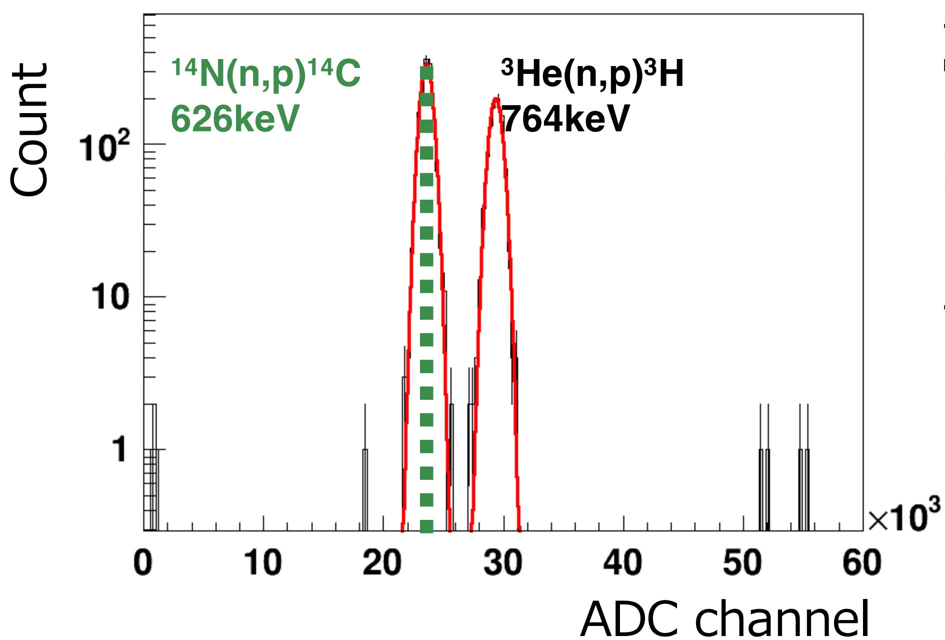
Gas No	^3He Partial pressure	Static Expansion (V1/V2) $^3He/^{14}N$	Direct by Baratron $^3He/^{14}N$
1	8.1 mPa*	$2.22(4)\times10^{-7}$	
2	9 Pa	$2.356(11)\times10^{-4}$	$2.354(10)\times10^{-4}$
3	21 Pa	$5.211(15)\times10^{-4}$	$5.203(12)\times10^{-4}$

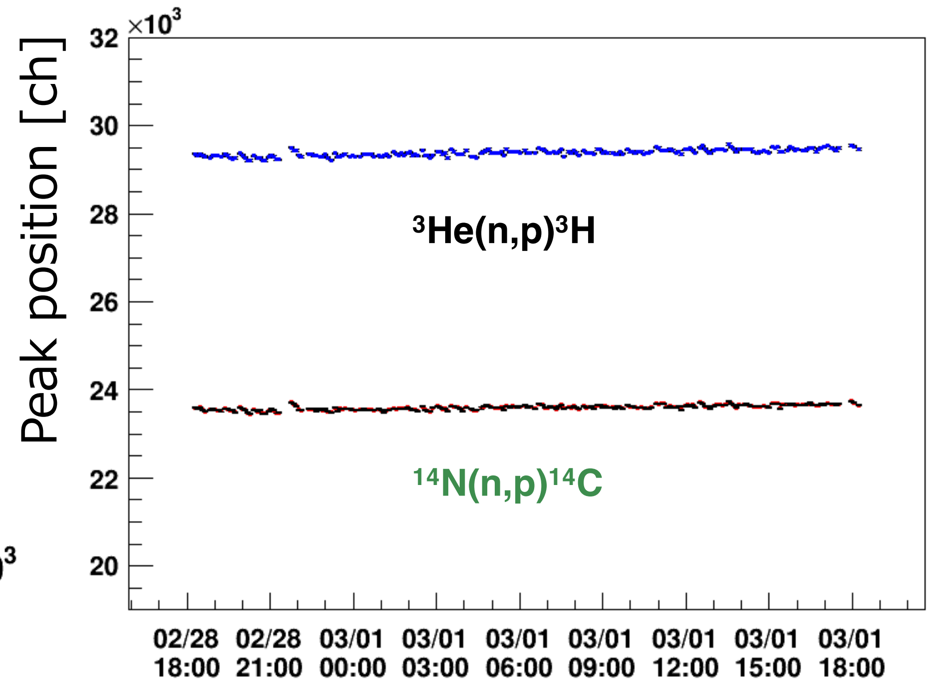
Pressure ratios determined by 2 method were consistent in uncertainties.

*^3He of Gas#1 is content of a commercial He bottle, which was measured by mass spectroscopy.

Energy calibration for elapsed time

The peaks positions were calibrated for each run (300 sec) as $^{14}N(n,p)^{14}C$ for 626keV.

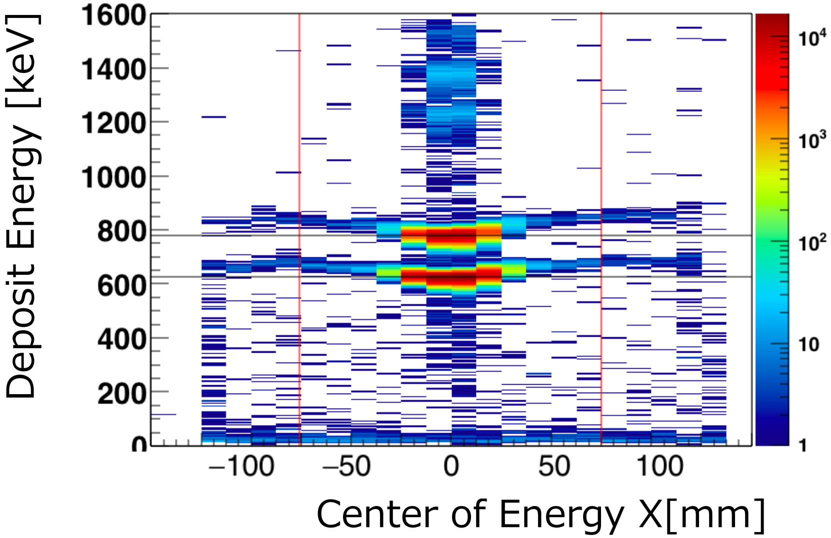


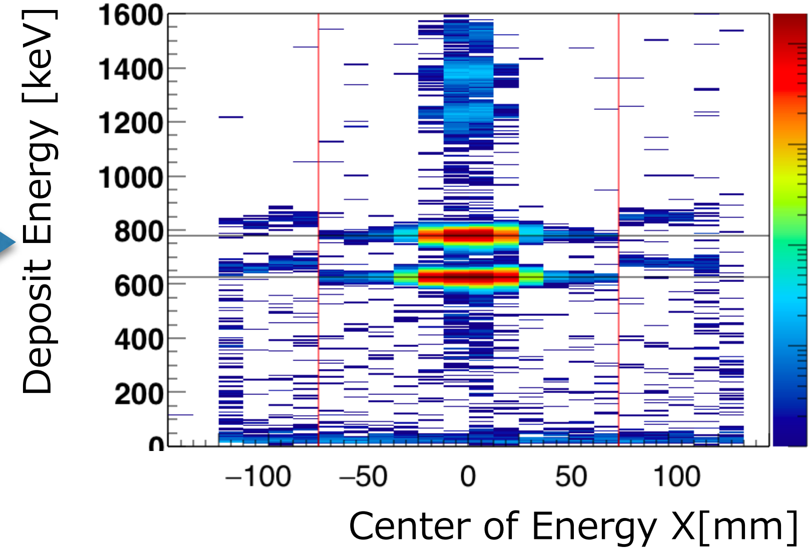


Energy calibration for position

X pos.

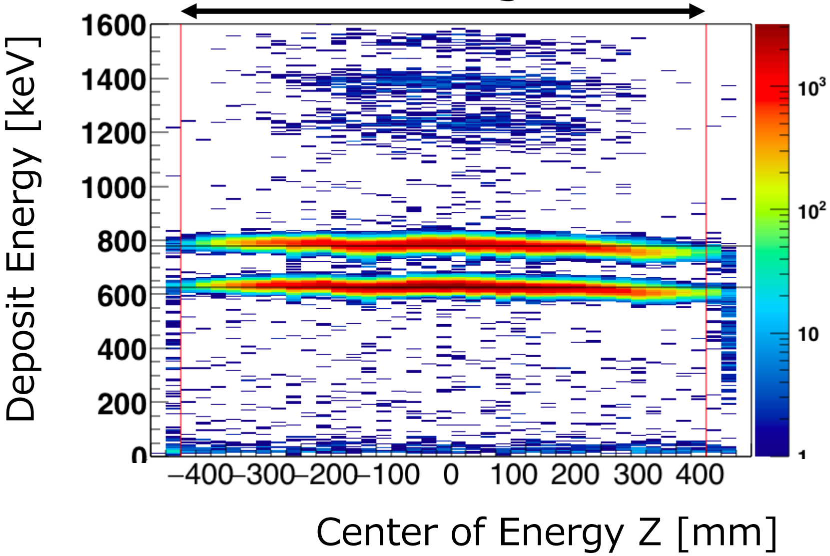
Cut region

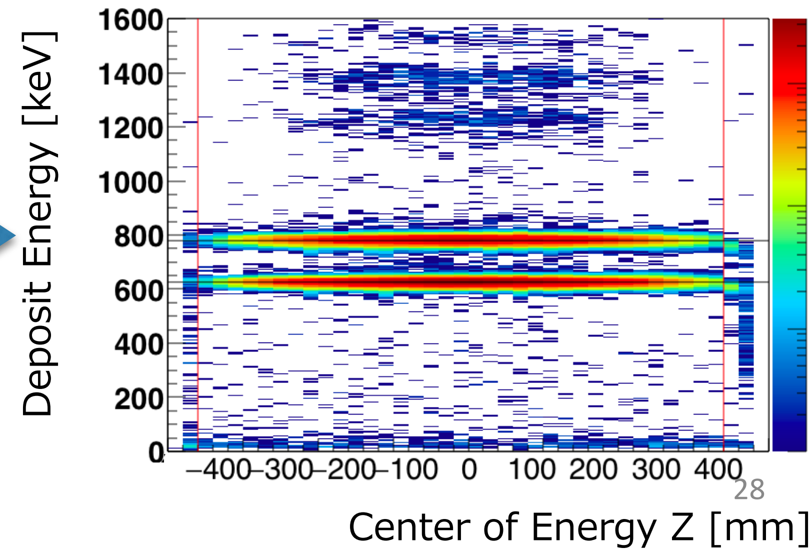




Z pos.

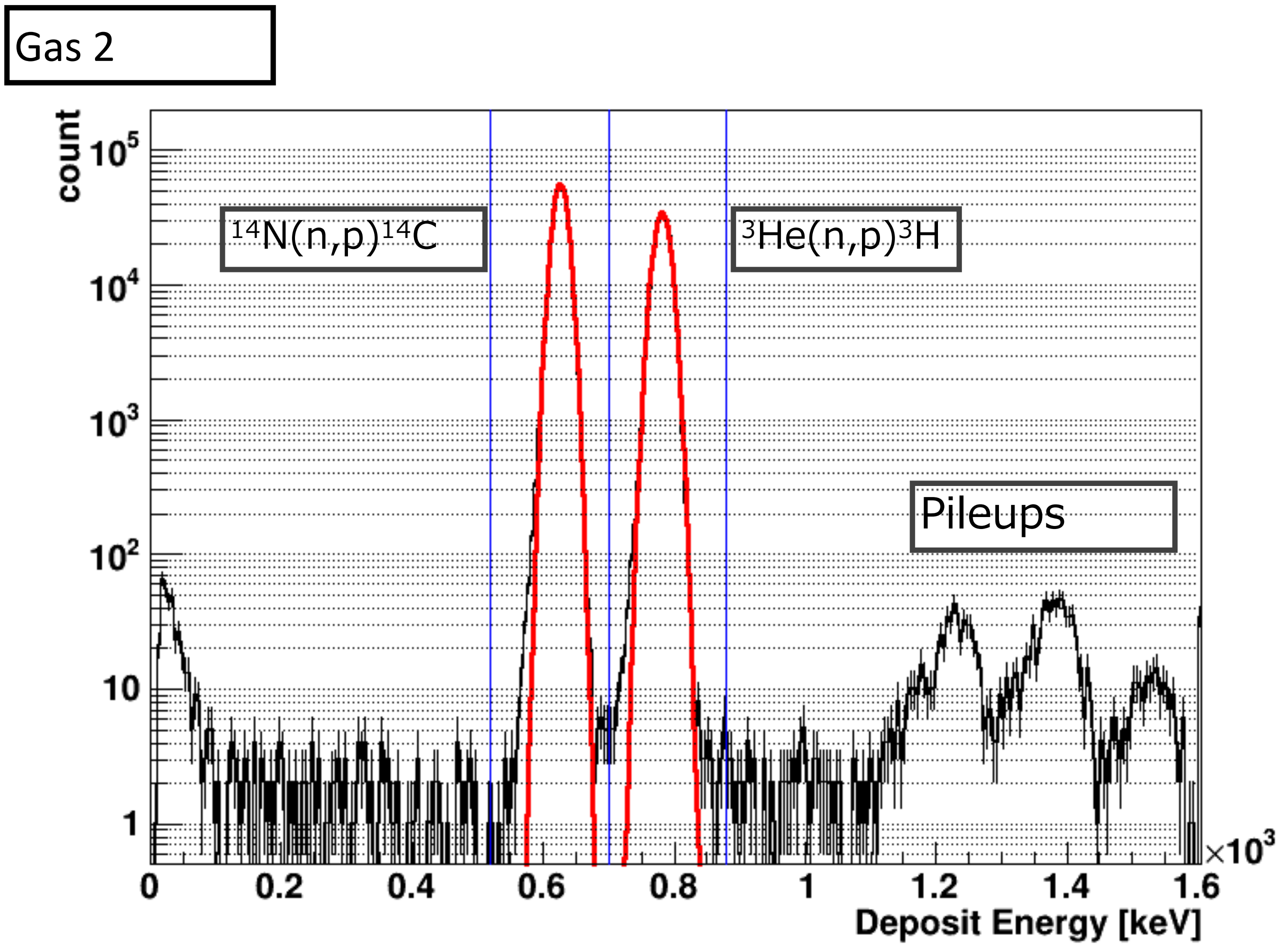
Cut region





Energy spectrum calibrated

For quick analysis, number of evens were counted for ^{14}N and ^{3}He in 520~700 keV and 700keV~880 keV, respectively. We are making response functions to evaluate counts of these peaks.

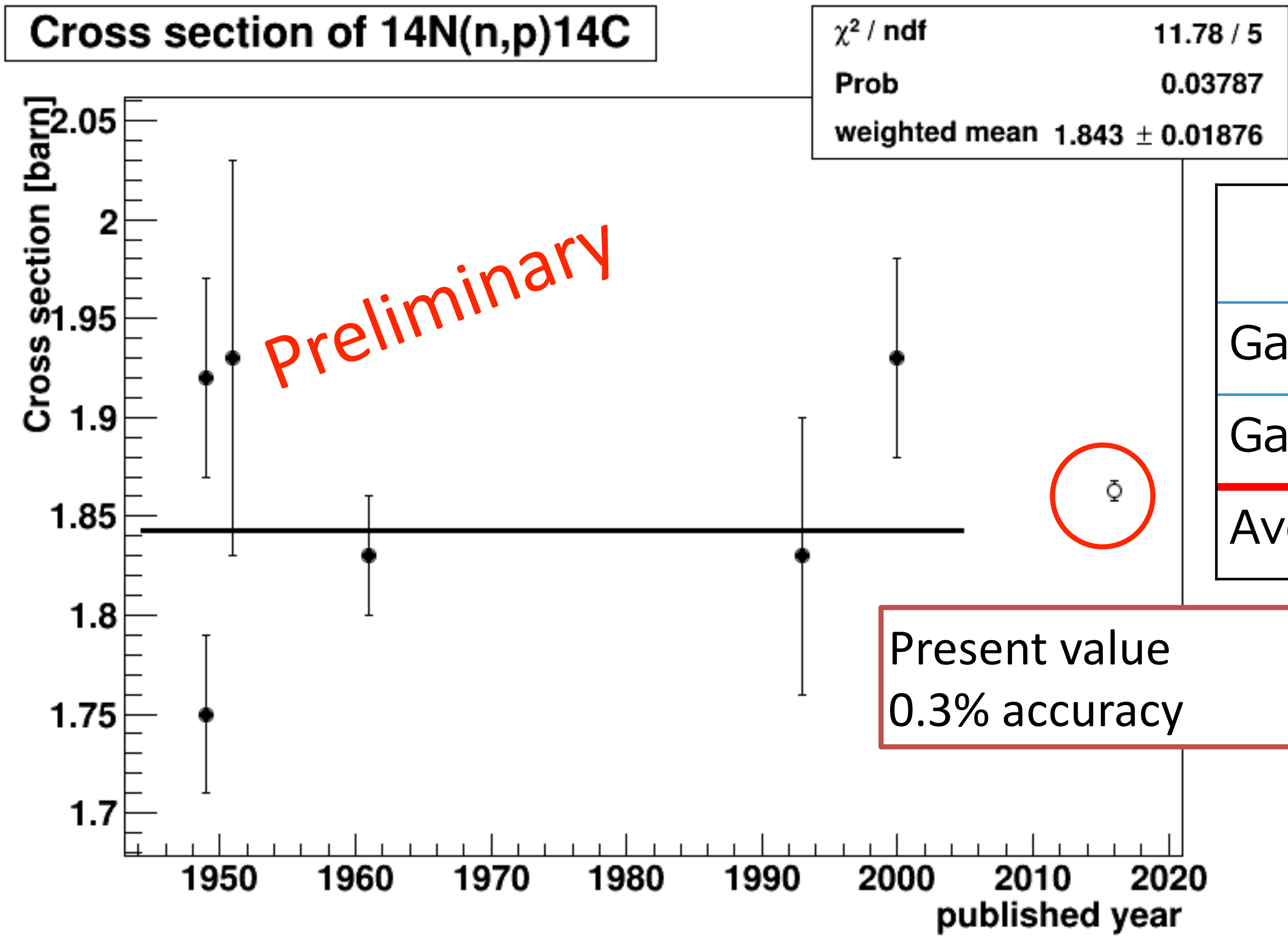


Error budgets

$$\sigma_{14N}(v_0) = \frac{\epsilon_{3He}}{\epsilon_{14N}} \frac{R_{14N}}{R_{3He}} \frac{\rho_{3He}}{\rho_{14N}} \sigma_{3He}(v_0)$$

			Gas 2		**Gas 3**	
Parameter		Effect	Correction[%]	Uncertainty [%]	Correction[%]	Uncertainty [%]
Efficiency	e_N	Escape to X direction	-0.013	0.013	-0.013	0.013
	e_N	Escape to Y direction	-0.067	0.067	-0.061	0.061
	e_N/e_{He}		**-0.08**	**0.08**	**-0.07**	**0.07**
Event rate	R_N	Statistic	0	0.18	0	0.13
	R_{He}	Statistic	0	0.22	0	0.11
		Distinction of 2 peaks	Being evaluated			
	R_N/R_{He}			**0.29**		**0.17**
Target number		Gas pressure and temperature	0	0.13	0	0.07
		Chemical purity of N_2 (specification)	-0.005	0.005	-0.005	0.005
		Abundance of ^{14}N (Literature values)	-0.3663	0.0004	-0.3663	0.0004
		Deformation of the chamber	-0.33	0.33	-0.07	0.07
	ρ_N		0.70	0.35	0.44	0.10
		^3He content in commarginal He gas	0	0.00175	0	0.0008
		Purity of ^3He (specification)	-0.05	0.05	-0.05	0.05
		Gas pressure and temperature	0	0.24	0	0.16
		Thermal transpiration effect of Baratron	-1.74	0.1	-1.08	0.1
	ρ_{He}			0.27		0.20
	ρ_{He}/ρ_N			**0.44**		**0.22**
$\sigma\,^3He(n,p)^3H$	**σ_{3He}**	**Literature values**	**0**	**0.13**	**0**	**0.13**
$\sigma\,^{14}N(n,p)^{14}C$				**0.55**		**0.32**

Comparison with previous results



	Cross section [barn]
Gas 2	1.871(10)
Gas 3	1.861(6)
Average	1.863(5)

Other (n,p) reactions

Reaction	Q value (keV)	Cross section	Uncertainty	Available Gas
$^{3}He(n,p)^{3}H$	763.76	5333(7) b[1]	0.13%	He
$^{10}B(n,p)^{10}Be$	225.55	6.8(5) mb[2]	7.4%	BF_3
$^{14}N(n,p)^{14}C$	625.87	1.83(3) b	1.6%	N_2
$^{33}S(n,p)^{33}P$	533.84	2(1) mb[1]	50%	SF_6
$^{35}Cl(n,p)^{35}S$	615.02	489(14) mb[1]	2.9%	CCl_4
$^{36}Ar(n,p)^{36}Cl$	72.82	< 1.5 mb[3]	1.8%	Ar

1. Richard B. Firestone eighth edition, "Table of isotope", John Wiley & Sons, Bradford, (1996)
2. Lal, D., et al., *Nuclear Physics A* 468.2 (1987): 189-192.
3. Jiang, S. S., et al. *NIMB* 52.3 (1990): 608-611.

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Summary

- Neutron decay parameters (lifetime and λ) are important parameter for
  - Big Bang Nucleosynthesis
  - Reactor neutrino anomaly
  - Solar neutrino
  - CKM unitarily
- We are measuring the neutron lifetime at J-PARC.
  - Our goal is 1 sec accuracy.
  - We obtained O(10) sec data. The first data will coming soon.
- We measured $^{14}N(n,p)^{14}C$ reaction cross section as 1.863(5) barn, 0.3% accuracy.
  - Other (n,p) reactions can be measured in the same manner.

Other (n,a) reactions

Reaction	Q value (keV)	Cross section	Uncertainty	Available Gas
$^{10}B(n,a)^{10}Be$	225.55	3837(9) b[1]		BF_3
$^{33}S(n,a)^{33}P$	3493.51	0.19(8) b[1]		SF_6
$^{35}Cl(n,a)^{35}S$	937.74	0.08 (4) b[1]		CCl_4
$^{36}Ar\ (n,p)^{36}Cl$	2000.72	5.5(1) mb[1]		Ar

1. Richard B. Firestone eighth edition, "Table of isotope", John Wiley & Sons, Bradford, (1996)
2. Lal, D., et al., *Nuclear Physics A* 468.2 (1987): 189-192.
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